ICONE
Conference Paper

ICONE10-22506

APPLICATION OF SEISMIC ISOLATION TO THE STAR-LM REACTOR

B. Yoo
Korea Atomic Energy Research Institute
Taejon, South Korea
E-mail: byoo@kaeri.re.kr

R. F. Kulak
Argonne National Laboratory
Argonne, IL, USA
E-mail: rfkulak@anl.gov

ABSTRACT

This paper presents findings from our initial work in developing a seismic isolation system for the STAR-LM reactor design. Research and development was carried out to determine the characteristics of the isolator device. The heavy weight and small footprint presented a challenge in bearing design and bearing placement. Results are also presented from a study on the use of three-dimensional seismic isolation devices to the full-scale reactor. Both two-dimensional (i.e., one device for horizontal isolation only) and integral (i.e., one device for horizontal and vertical) concepts were explored. The seismic analysis responses of the two-dimensional and the three-dimensional isolation systems for the STAR-LM are compared with that of the conventional fixed base system. Finally, results are presented from a study on the effects of the levels of vertical and horizontal damping on the seismic response of STAR-LM.

INTRODUCTION

The next generation of nuclear energy systems will be the result of the Generation IV program, which has the following goals: sustainability, safety and reliability, and economics. Because Gen IV reactor plants will be deployed worldwide, some plants will be located in seismically active regions as well as seismically active countries. Thus, one of the major challenges placed before the designers of Gen IV plants is to design the plants not only to survive seismic events but also to continue to provide power during and after earthquakes. Passive seismic isolation is the leading candidate for achieving this goal.

Several designs, which use liquid metal coolants, have been proposed as part of the Generation IV program: STAR-LM (300-400 MWth), ENHS (125 MWth), KALIMER (150-330 MWe) and S-PRISM (1000 MWth). STAR-LM and ENHS use a lead-bismuth eutectic as the coolant, and KALIMER and S-PRISM use liquid sodium as the coolant. The use of lead-bismuth eutectic (1) results in plant simplification, (2) improves cost competitiveness, (3) increases inherent/passive safety, and (4) provides achievable proliferation resistance measures. However, lead coolant is ten times heavier than sodium coolant and this present a challenge to designers of the seismic isolation systems that will be used with these heavy liquid metal reactors.

Seismic isolation systems have been fully developed and designed for the sodium cooled KALIMER and S-PRISM concepts. Much research was performed on their isolation systems (1) to quantify elastomer response characteristics, (2) to identify optimal mounting methods and (3) to determine system and isolator design parameters. There has not been any work done on the lead cooled designs.

This paper presents findings from our initial work in developing a seismic isolation system for the STAR-LM reactor design. Research and development was carried out to determine the characteristics of the isolator device. The heavy weight and small footprint presented a challenge in bearing design and bearing placement. Results are also presented from a study on the use of three-dimensional seismic isolation devices to the full-scale reactor. Both two-dimensional (with one device for horizontal isolation only) and three-dimensional (with one integral device for both horizontal and vertical isolation) concepts were explored. The seismic analysis responses of the two-dimensional and the three-dimensional isolation systems for the STAR-LM are compared with that of the conventional fixed base system.
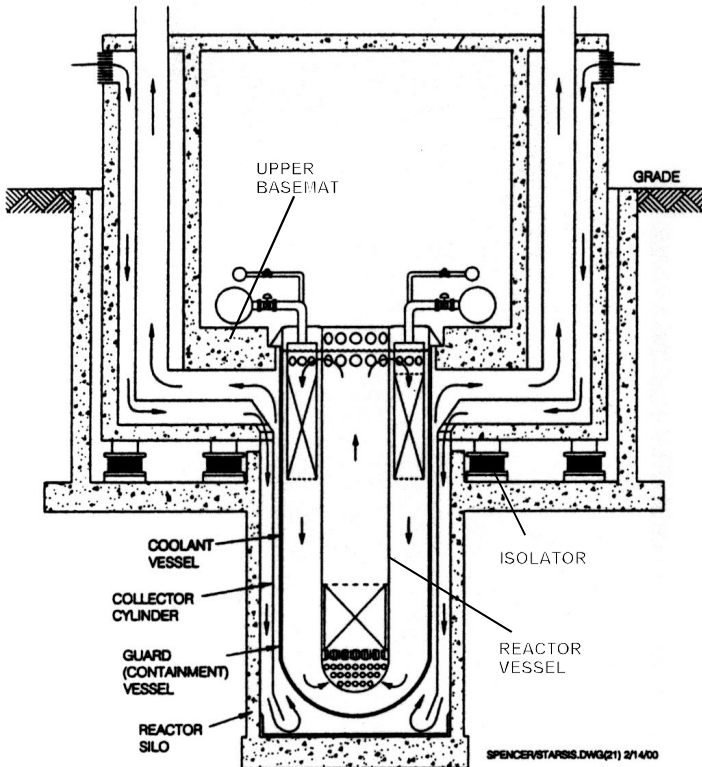
Figure 1. Design Configuration of STAR-LM with Seismic Base Isolation

Figure 2. Schematic Drawing of Three-Dimensional Seismic Isolation Device

PHYSICAL CHARACTERISTICS OF STAR-LM

The Secure, Transportable, Autonomous Reactor-Liquid Metal (STAR-LM), which is described in [1-4], is a small reactor module for steam supply of 300 MWth using lead-bismuth as a heavy liquid metal coolant. The reactor structure for STAR-LM includes a reactor module, four steam generators, a coolant module and a guard vessel and is shown in Figure1. The reactor module consists of the integral core assembly, steel shielding and reflector structures, and the reactor vessel. The module is suspended and sealed into the coolant module from its top head and a welded stainless steel. The outside diameter of the reactor module is 2.8m, and the length and the thickness of the module are assumed to be 12.65m and 5.0cm, respectively. The coolant module consists of the coolant vessel, coolant vessel liner, internal structures for positioning the reactor and steam generator modules, top head penetrations for inserting and sealing the reactor and SG modules, and piping. The coolant vessel, which is a welded structure of stainless steel, has the following overall dimensions: 5.5m outside diameter, 14m height and 5cm thickness. The coolant vessel is contained in a guard vessel with the following dimensions: 5.85m outside diameter, 14.2m length and 2.5cm thickness. The total weight of the reactor structure without and with the coolant inside of the coolant module are about 400 tons and 3100 tons, respectively.
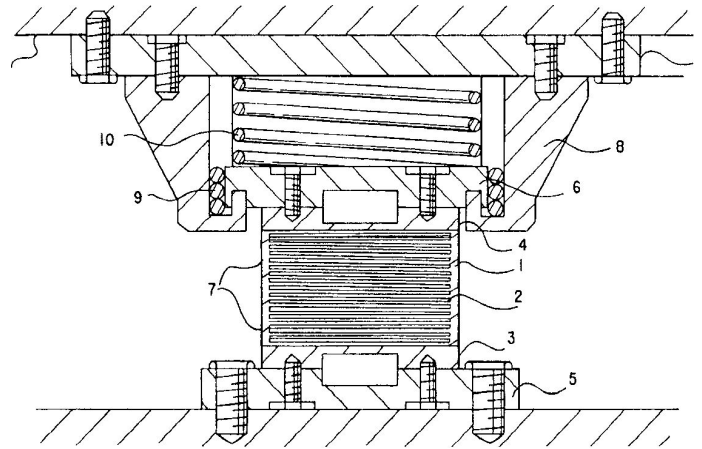
SEISMIC BASE ISOLATION SYSTEMS FOR STAR-LM

The nuclear island in which the reactor structure is contained is designed to be a seismically base isolated reactor building with Safe Shutdown Earthquake (SSE) of 0.3g in horizontal direction and 0.2g in the vertical direction, respectively. However the reactor building is not conceptually designed yet. In this paper it is assumed that all reactor structures are supported on the concrete basemat as a part of the nuclear island. The diameter of the basemat is taken to be 20m and the thickness is taken to be 1.5m. The basemat is supported on the seismic base isolation system. The total weight of the basemat including reactor structure with the coolant is about 4200 tons.

Two cases were considered for the base isolation systems of the STAR-LM concept: one for a two-dimensional seismic isolation system using horizontal laminated rubber bearings and the other for a three-dimensional seismic isolation system. The seismic responses for the seismic base isolation systems are compared with that of the conventional fixed base system

In the two-dimensional seismic isolation system, high damping laminated rubber bearings [5], similar to that in PRISM [6] and in KALIMER [7,8] are used. The vertical design load is selected to be 320 tons and the horizontal isolation frequency and the vertical frequency were determined to be 0.5 Hz and 21 Hz respectively. Design displacement in the horizontal direction is 27.8cm. The design quantities for the isolators are 120cm outside diameter and 50cm overall height, 29 rubber layers alternating with 28 layers of steel, and 27.8cm total rubber height. The design targets for the isolators are 12% above the damping coefficient and 300% above the maximum shear displacement.

In the three-dimensional seismic isolation system, the three-dimensional isolator [9] shown in Figure 2 is used in which the high damping laminated rubber bearing adapted to isolate horizontal seismic loadings cooperates with a vertical isolation device employing a series of disc springs effective for isolating vertical seismic loadings. The three-dimensional isolator is

effective to reduce both vertical and horizontal seismic loadings to insure the structural integrity of the reactor structure enhancing structural safety margin as well as the economic competitiveness. The vertical design load and the horizontal isolation frequency are 320 tons and 0.5 Hz respectively as same as the two-dimensional isolator. But the vertical isolation frequency is determined to be 1.1Hz such that the amplification factor in the vertical design response spectra at 5 % damping factor of NRC RG 1.60 is not greater than the maximum vertical ground acceleration. The vertical design displacement is 18.3cm.

The isolator consists of the series of disc springs located on the top of the upper end plate of the laminated rubber bearing (LRB), the isolation cylinder fixed to the base mat, and a number of groups of steel balls being disposed within a space formed between the perimeter of the upper end plate of LRB and the interior wall of the isolation cylinder. The balls are facilitating the guide for the relative vertical movement between the upper end plate and the isolation cylinder. The lateral seismic loads are transmitted to the basemat thru LRB, balls, and isolation cylinder. The design quantities for the disc spring for the three-dimensional isolator is 100cm outside diameter by 50cm inside diameter with 4.83cm thickness and 2.29cm cone height. The disc springs with 2 parallel and 18 series are used for the vertical isolation.

SEISMIC RESPONSE ANALYSES

The coolant vessel including the lead-bismuth coolant is modeled by a lumped mass beam model. For this preliminary study, the heavy metal coolant is lumped at the bottom of the coolant vessel, the concrete base mat is modeled as a lumped mass, and the two-dimensional and the three- dimensional isolation systems are properly modeled by the equivalent stiffness and the equivalent viscous damping to represent mechanical properties of the isolators. The input motions used for the time history analyses are three components of the artificial time history, which are compatible with the USNRC RG 1.60 design response spectra. The vertical input motion has a minimum and maximum acceleration of ñ2.22~1.95m/sec2, a duration of 76 seconds with time step of 0.01 second, and the horizontal input motions have ñ3.07~2.94 and ñ3.14~2.94m/sec2, respectively, the duration of 80 seconds with time step of 0.01 second. The analyses were performed using SAP2000 v7.4.

Table 1 shows the calculated natural frequencies for the fixed base, the two-dimensional and the three-dimensional isolation case. Natural frequencies of the fixed base are 2.9Hz in the Y and Z horizontal directions and 11.9Hz in the X vertical direction, respectively. The isolation frequency of the two-dimensional isolation case is 0.5Hz in the Y and Z horizontal directions and the first structural frequencies are 5.1Hz in the Y and Z horizontal directions and 10.7Hz in the X vertical direction. For the three-dimensional case, the isolation frequencies are 0.5Hz in the Y and Z horizontal directions, which are the same as the two-dimensional isolation case, and 1.1Hz in the X vertical direction. The first structural frequencies are 5.1Hz in the Y and Z horizontal
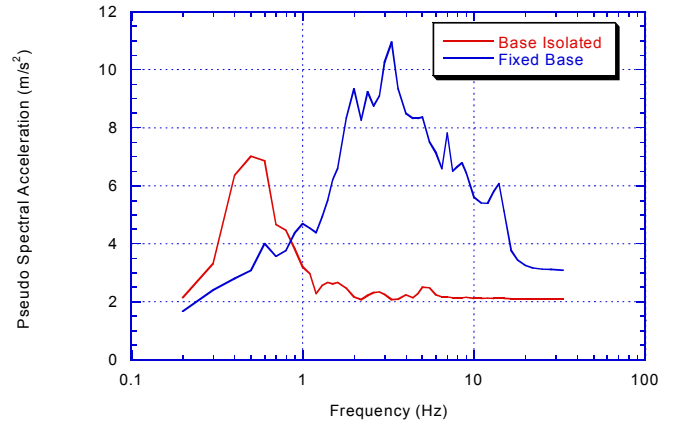
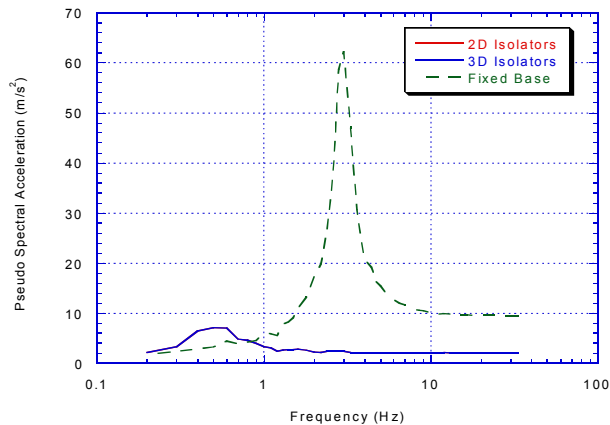*Horizontal Response Spectra at Upper Basemat*
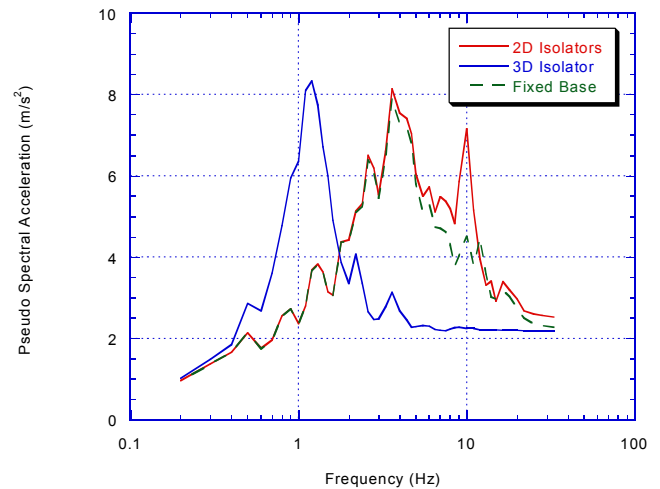
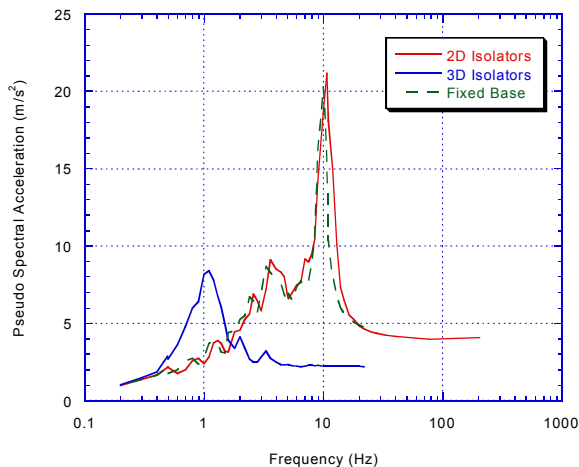*Vertical Response Spectra at Upper Basemat*

Figure 3. Floor Acceleration Response Spectra at Upper Basemat for Fixed Base, Two-Dimensional and Three-Dimensional Isolation Systems

directions and 20.5 Hz in the X vertical direction, respectively.

Figures 3 and 4 compare the acceleration floor response spectra at a damping value of 5% at the upper basemat and the bottom of the coolant vessel for the three cases when subjected to the same input motions. In the horizontal direction, the floor accelerations for the two-dimensional and the three-dimensional isolation cases become much lower than those of the fixed base case such that reductions from 9.3m/sec^2 to 2.3m/sec^2 are obtained at the upper basemat and from 49.54m/sec^2 to 2.31m/sec^2 at the bottom of the coolant vessel, respectively. In the vertical direction, the floor acceleration of the three-dimensional case is reduced much lower than those of the two-dimensional and the fixed base cases. The floor accelerations for the two-dimensional case are slightly amplified over those of the fixed base case. The reduction of the

3   Copyright ©2002 by ASME

Horizontal Response Spectra at Bottom of Coolant Vessel

Vertical Response Spectra at Bottom of Coolant Vessel

Figure 4. Floor Acceleration Response Spectra at Bottom of Coolant Vessel for Fixed Based, Two-Dimensional and Three-Dimensional Isolation Systems

floor accelerations of the three-dimensional isolation system is from 6.7m/sec^2 of the fixed base, and 6.92m/sec^2 of the two-dimensional isolation case, to 2.93m/sec^2 at the upper basemat, and from 16.34m.sec^2 of the fixed case, and 16.61m/sec^2 of the two-dimensional isolation case, to 2.23m/sec^2 at the bottom of the coolant vessel, respectively. The calculated seismic responses of the acceleration time history and the isolator displacement for the three cases are summarized in Table 2.

For the two- and the three-dimensional isolation systems, the shear displacements at the LRB are calculated as the same values as a minimum and maximum of ñ18.67~19.97cm, which is equivalent to the shear strain of 109%, in the Y horizontal direction, and ñ15.01~16.76cm, in the Z horizontal direction, respectively. For both the two-dimensional isolation system and the fixed base case, there is little relative motion in the vertical

direction. In contrast for the three- dimensional isolation system, the relative displacement at the vertical disc springs is calculated as a minimum and maximum of ñ4.39~2.94cm in the X vertical direction, which is within the design requirement value of 18.3cm.

EFFECTS OF DAMPING ON SEISMIC RESPONSE

The effects of damping on the seismic responses of three dimensional isolation system are investigated using time history analyses and varying the damping values of the isolation system. The following damping values were used in the analyses: 12, 24, 36, 48 and 60% in the horizontal direction, and 8, 16, 24, 32 and 40% in the vertical direction.

The maximum peak accelerations at both the reactor upper mat and at the bottom of the coolant vessel were gradually reduced in all three directions, as the damping value of the isolation system is increased. Similarly, the maximum shear displacement is reduced as the damping value increases. Table 3 shows the effects of the value for horizontal damping on the peak acceleration and maximum shear strain. It is seen that at 12% horizontal damping the peak acceleration is 3.940 m/sec^2 and the maximum shear displacement is 19.97 cm. At 60% damping, the peak acceleration reduces to 3.333 m/sec^2 and the maximum shear displacement reduces to 9.29 cm. Table 4 shows the reductions in the vertical response as the damping values increase.

The relative displacement between the upper mat and the bottom of the coolant vessel is very small: 5.9 mm for 12% damping in the horizontal direction and 0.3 mm for 8% damping in the vertical direction, which shows the rigid body motion of the primary reactor is maintained during the earthquake excitation. The relative displacement between the upper mat and the bottom of the coolant vessel is reduced to 2.32 mm from 5.9 mm in the horizontal direction and from 0.3 mm to 0.2 mm in the vertical direction, as the damping is increased to 60 % in the horizontal direction and 40% in the vertical direction. These small relative displacements between the shutdown rod and the core fuel assemblies and the rigid body motion of the reactor can be very important for the safety insertion of shutdown rod into the reactor core and to reduce the change of reactivity worth by reducing the compaction of the core fuel assemblies.

Figure 5 shows that increasing the damping of the isolators increases the floor accelerations to some extent in the frequency range of 1.5 Hz to 5 Hz. For the case with 60% damping in the horizontal direction and 40% damping in the vertical direction, a maximum acceleration of 3.4 m/s^2 occurs at a frequency of 2 Hz.

CONCLUSION

The effectiveness of the application of the isolation systems to the STAR-LM Generation IV reactor is presented by comparing the seismic responses subjected to the artificial time histories among the fixed base, the two-dimensional isolation system using LRB, and the three-dimensional isolation system using the integral isolators. The following are the conclusions from the study.
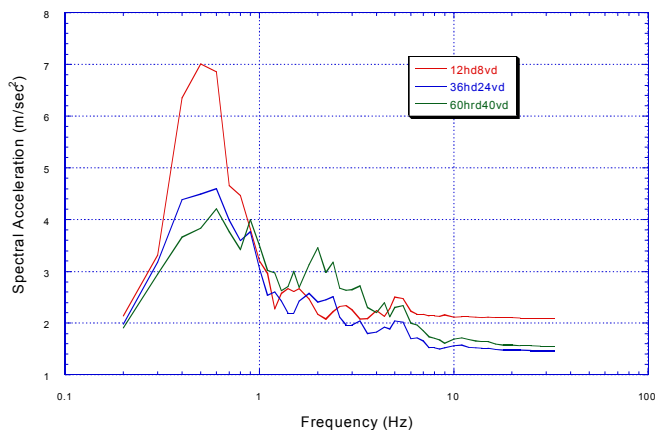
Figure 5. Effect of Damping on the Floor Horizontal Acceleration Response Spectra at Upper Basemat for Three-Dimensional Isolation System

When compared with the conventional fixed base design, the two-dimensional and the three-dimensional isolation systems can reduce the floor accelerations in the horizontal direction by a factor of 4 at the upper basemat and a factor of 20 at the bottom of the coolant vessel. The three-dimensional isolation system can reduce the floor accelerations in the vertical direction by a factor of 2.4 at the upper basemat, and a factor of 7.4 at the bottom of the coolant vessel, when compared to the fixed base and the two-dimensional system.

The maximum shear displacement for the two and the three-dimensional systems is calculated as 19.97cm, equivalent to 109% shear strain, which is well within the maximum shear failure limit of 300%. The maximum relative displacement in the vertical direction for the three-dimensional isolation system is calculated as 4.39cm, which is also well within the design limit of 18.3cm.

The application of seismic isolation to the STAR-LM reactor results in the reduction of the horizontal floor accelerations at the upper basemat with the two-dimensional LRB, and in the reduction of the horizontal as well as vertical floor accelerations at the upper basemat with the three-dimensional isolators. This could provide a safety margin for the structural integrity and the economic designs for the reactor structures for the STAR-LM.

Increasing the damping values of the isolators can result in reducing the clearances between the isolated reactor system and the surrounding non-isolated structures but increases the floor accelerations to some extent in the frequency range of 1.5Hz to 5Hz. Through further design of the STAR-LM concept, the dynamic characteristics of the safety related components attached to the reactor upper mat and the detail analyses of the isolated primary reactor will help to determine the optimal damping of the three dimensional system for the seismic design of STAR-LM.

Further studies are needed to verify the performance of the full-scale three-dimensional isolation system subjected to the design and the beyond design basis earthquakes and to solve the potential rocking issue of the three-dimensional isolation system.

REFERENCES

[1] Spencer B.W. et al., 2000, ì*An advanced modular HLMC reactor concept featuring economy, safety, and proliferation resistanceî* , icone-8145, ICONE 8, U.S.A.

[2] Sienicki, J. J. and Spencer, B. W., ì*Power Optimization in the STAR-LM Generation IV Modular, Natural Convection Reactor System,*î Paper No. ICONE 10-22294, Proceedings Tenth International Conference on Nuclear Engineering, Arlington Virginia, April 14-18, 2002.

[3] Sienicki, J. J. and Petkov, P. V., ì *Autonomus Load Following and Operational Aspects of the STAR-LM HLMC Natural Convection Reactor,*î Paper No. ICONE 10-22291, Proceedings Tenth International Conference on Nuclear Engineering, Arlington Virginia, April 14-18, 2002.

[4] Sienicki, J. J. and Petkov, P. V. Spencer, B. W., ì*Passive Safety of the STAR-LM HMLC Natural Convection Reactor,*î Paper No. ICONE 10-22290, Proceedings Tenth International Conference on Nuclear Engineering, Arlington Virginia, April 14-18, 2002.

[5] Kulak, R. F., 1996, "Key Findings from R & D Activities at Argonne National Laboratory for Seismic Isolation Bearings," Eds., H. H. Chung and M. A. Saleem, <u>Seismic, Shock, and Vibration Isolation-1996</u>, ASME Publication PVP-Vol. 341, pp. 31-35.

[6] Gluekler E.L. et al., 1995, ì*New R&D for isolated nuclear facilities in the U.S.A.*î, 13th Post SMIRT Seismic isolation, passive energy dissipation and active control of seismic vibrations of structures, p.291-301, Chile, August 21-23.

[7] Kelly J.M. et al., 1997, ì*Experimental testing of reduced-scale seismic isolation bearings for nuclear application*î , 14th Post SMIRT Seismic isolation, passive energy dissipation and active control of seismic vibrations of structures, p.485-514, Italy, August 25-27.

[8] Yoo B. et al., 2000, ì*Seismic base isolation technologies for Korea advanced liquid metal reactor*î , Nuclear Engineering and Design 199, p.125-142.

[9] Yoo B. et al., 1999, ì*Integrated horizontal and vertical seismic isolation bearing*î , United States Patent, patent number 5881507, March 16.

Table 1. Frequency Analysis Results of STAR-LM Structure Models

Mode	Fixed Base		2-D Isolation		3-D Isolation	
	Frequency (Hz)	Modal Participation Mass Ratio	Frequency (Hz)	Modal Participation Mass Ratio	Frequency (Hz)	Modal Participation Mass Ratio
Horizontal Isolation (Y &Z)	-	-	0.5	99.99	0.5	99.98
Vertical Isolation (X)	-	-	-	-	1.1	99.99
1st Y Structural	2.9	98.22	5.1	0.018	5.1	0.018
1st Z Structural	2.9	98.22	5.1	0.018	5.1	0.018
1st X Structural	11.9	99.66	10.7	78.18	20.5	0.002

Table 2. Comparison of STAR-LM Seismic Responses for Fixed Base, 2D-Isolation and 3D-Isolation

	Fixed Base		2D Isolation		3D Isolation	
	Horizontal (Y)	Vertical (X)	Horizontal (Y)	Vertical (X)	Horizontal (Y)	Vertical (X)
Upper Basemat Peak Acceleration (m/sec^2)	-3.073~ 2.94	-2.221~ 1.953	-3.68~ 3.94	-2.467~ 2.17	-3.68~ 3.94	-2.98~ 2.60
Coolant Vessel Bottom Peak Acceleration (m/sec^2)	-9.086~ 9.118	-2.535~ 2.456	3.742~ 4.129	-2.78~ 2.78	-3.742~ 4.129	-3.013~ 2.628
Isolator Displacement (cm)	-	-	-18.67~ 19.97	-0.019~ 0.019	-18.67~ 19.97	-4.39~ 2.94

(Subjected to SSE: 0.3g in the horizontal direction and 0.2g in the vertical direction, 1.0g = 9.8m/sec^2)

Table 3. Effects of Horizontal Damping on Peak Acceleration and Maximum Shear Strain

Horizontal Damping (%)	Peak Horizontal Acceleration (m/sec^2)	Maximum Shear Displacement (cm)
12	3.940	19.97
24	3.868	14.44
36	3.686	12.05
48	3.497	10.47
60	3.333	9.29

Table 4. Effects of Vertical Damping on Peak Acceleration and Maximum Vertical Displacement

Vertical Damping (%)	Peak Vertical Acceleration (m/sec^2)	Maximum Vertical Displacement (cm)
8	2.980	4.39
16	2.723	3.51
24	2.499	2.958
32	2.318	2.598
40	2.169	2.347